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DYNAMIC SPATIAL FILTERING OF DEFORMABLE MIRROR COMMANDS FOR MITIGATION OF THE WAFFLE MODE (Postprint)

Kevin P. Vitayaudom, et. al

Air Force Research Laboratory
3500 Aberdeen Ave SE
Kirtland AFB, NM 87117

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AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
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Kevin P. Vitayaudom; Darryl J. Sanchez; Denis W. Oesh*; Patrick R. Kelly; Carolyn M. Tewksbury-Christle; Julie C. Smith

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Dynamic spatial filtering of deformable mirror commands for mitigation of the waffle mode

Kevin P. Vitayaudom[a], Darryl J. Sanchez[a], Denis W. Oesch[b], Patrick R. Kelly[a], Carolyn M. Tewksbury-Christle[a], and Julie C. Smith[a]

[a]Air Force Research Laboratory, 3550 Aberdeen Ave SE, Kirtland AFB, NM;
[b]Science Applications International Corp., Albuquerque, NM

ABSTRACT

The conventional adaptive-optics (AO) system configuration consisting of a Shack-Hartmann wavefront sensor using the Fried geometry is prone to an unsensed waffle mode because of an inability to have discrete point reconstruction of the phase at the actuator positions. Techniques that involve filtering and/or projecting out the waffle mode in the reconstructor have been shown to be effective at not allowing the unwanted mode to occur, but come at the cost of also omitting relevant high frequency content from the measured phase. This paper analyzes a technique of sensing the waffle mode in the deformable mirror commands and applying a spatial filter to those commands in order to mitigate for the waffle mode. Directly spatially filtering the deformable mirror commands gives the benefit of maintaining the reconstruction of high frequency phase of interest while having the ability to alleviate for the waffle pattern when it arises.

Keywords: adaptive optics, waffle mode, spatial filtering

1. INTRODUCTION

The waffle pattern is a mode that goes unsensed in many conventional adaptive-optics systems that use the Shack-Hartmann wavefront sensor (SH WFS) and Fried sampling geometry to measure and reconstruct the phase at the actuator positions of the deformable mirror (DM). When this mode goes unsensed, it is not corrected by the DM and can accumulate within the closed-loop operation of the system. During night testing conducted at the Air Force Research Laboratory (AFRL), Starfire Optical Range, Kirtland AFB, NM, this waffle has been observed on their 3.5 meter telescope AO system. When this mode accumulates, the adaptive-optics operator opens the feedback loop of the system in order to clear the DM commands and alleviate the waffle. However, the discontinuation of closed-loop adaptive-optics imaging is undesirable during data acquisition runs. The AFRL's Sodium Guidestar Adaptive Optics for Space Situational Awareness Program (NGAS) is updating the AO system on the SOR's 3.5 meter telescope and sponsored research into techniques to mitigate for the waffle when there is an accumulation on the DM. This paper will discuss a technique of sensing the waffle by correlating the DM commands with a known waffle pattern and mitigating the waffle, when it occurs, by spatially filtering those commands. The technique will then be evaluated experimentally in order to determine its utility for an operational AO system.

Several authors have explored different approaches for suppressing the waffle mode behavior in adaptive-optics systems. Gavel introduced a technique using singular value decomposition to modally segregate and penalize the waffle behavior, thereby suppressing the waffle from being reconstructed in the wavefront solution.[1] There has also been work in spatially filtering the reconstruction matrix which attenuates high spatial frequency content, decreasing sensitivity to misregistration and the occurrence of waffle.[2] These techniques are effective at not allowing waffle to build, yet subsequently suppress the spatial frequency content that is associated with this particular mode. The Hudgin sampling geometry could also be utilized and is sensitive to the waffle pattern, yet we used the Fried geometry to match the NGAS program which sponsored this research.[3] This paper will present a technique that only alleviates for the waffle when it is detected and does not effect the reconstruction of the phase when the mode has not accumulated to a degree that causes degradation in the performance of the system.

The next section will discuss how the waffle mode develops and why it goes unsensed using the Fried geometry coupled with the SH WFS. Section 2 will detail the method used to sense the waffle mode when it develops on

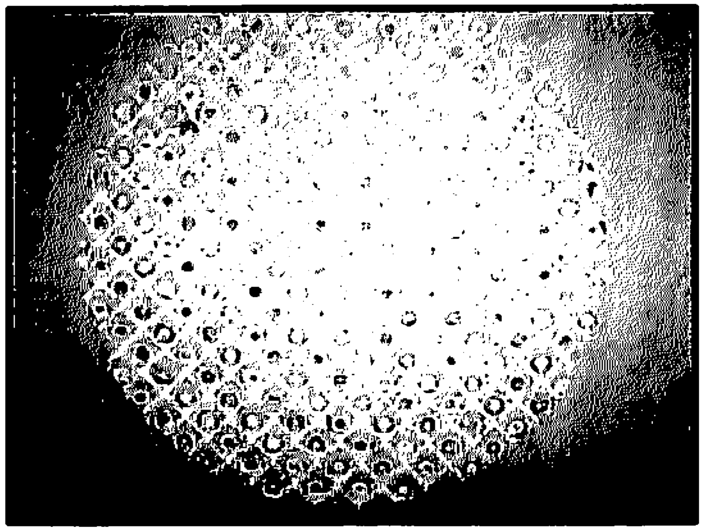

Figure 1. Waffle mode over a DM. An interferogram over a DM is shown with the actuators commanded to the waffle pattern.

the commands sent to the DM. Then in Section 3 the method for spatially filtering the DM commands when the waffle is sensed will be discussed. Section 4 presents the optical bench setup that was used to conduct the experiments. The results and analysis of those experiments are given in Section 5. Section 6 presents the conclusions from this research.

2. WAFFLE MODE

Waffle is a prevalent unsensed mode which can lead to unwanted commands sent to the DM. WFSs with square subapertures aligned to the corner-positions of a DM coupled with a Fried geometry reconstruction method is particularly susceptible to this mode, as shown in Figure 1. The Fried geometry has no cross-coupling in the discrete-point reconstruction of the phases on the actuators, detailed in Section 2.1. This allows piston differences between two independent actuator spaces to be unsensed in the reconstruction of the phase.

2.1 Unconstructed waffle mode using the Fried geometry

SH WFSs cannot measure phase directly. Instead, it measures wavefront gradients over each subaperture. The gradients from the SH WFS are used to piece together a map of the phase so that it can be used with the servo-controller for the DM. There are multiple alignment geometries that give the registration between the actuators and the WFS subapertures such as the Hudgin geometry, Southwell geometry, and Fried geometry. Each of the geometries has its own characteristics that affect the stability of the control system, but the Fried geometry is used for this research. The Fried geometry is a common choice in many AO systems because of the low computational complexity and its relation to square detector arrays. The Fried geometry defines the relationship between the relative slopes over each subaperture measured by the SH WFS and the phase of the actuators at the corners of the subaperture. Figure 2 is a depiction of the Fried geometry over a subaperture where $\varphi_{n,m}, \varphi_{n+1,m}, \varphi_{n,m+1}$,and $\varphi_{n+1,m+1}$ are the phases at the actuator locations and the subscripts (n, m) designate a specific actuator position. The Fried Geometry gives a direct relationship between the measured x and y slopes of the subaperture $(s_x)_{n,m}$ and $(s_y)_{n,m}$, and phase at the actuator locations given by

$$(s_x)_{n,m} = \frac{1}{2}(\varphi_{n+1,m} - \varphi_{n,m}) + \frac{1}{2}(\varphi_{n+1,m+1} - \varphi_{n,m+1}), \quad (1)$$

$$(s_y)_{n,m} = \frac{1}{2}(\varphi_{n,m+1} - \varphi_{n,m}) + \frac{1}{2}(\varphi_{n+1,m+1} - \varphi_{n+1,m}). \quad (2)$$

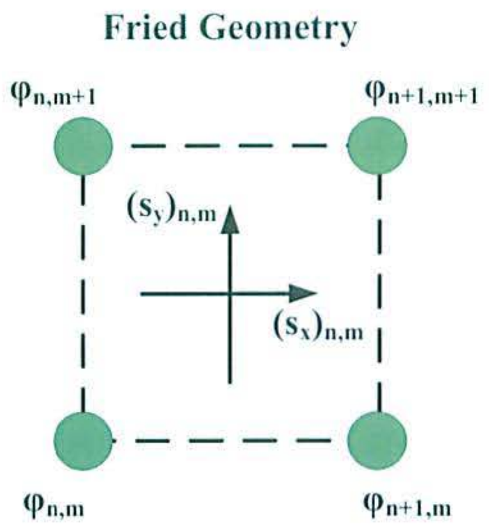

Figure 2. Fried geometry. The slope measurements over the subaperture are used to estimate the phase at the corner actuator positions.

The waffle pattern occurs when the phase between actuators are sensed to be zero when in actuality they have piston differences between them.[4] For example, in the simplified case where the actual phase at the actuator positions are $\varphi_{n,m} = 1$ μrad, $\varphi_{n+1,m} = -1$ μrad, $\varphi_{n,m+1} = -1$ μrad, and $\varphi_{n+1,m+1} = 1$ μrad, the calculated slopes using Eqs. (1) and (2) would be zero for $(s_x)_{n,m}$ and $(s_y)_{n,m}$. The piston differences between the phase at the actuator positions are not represented in the calculated slopes so they cannot be reconstructed.

Due to the large magnitude of actuators that are used, Eqs. (1) and (2) can be represented in matrix form for computational simplicity,

$$\mathbf{s} = \mathbf{A}\varphi, \tag{3}$$

where $\mathbf{s}$ represents the measured slopes over each subaperture, $\mathbf{A}$ is the Fried geometry's mathematical relationships, and φ represents the phase of the wavefront over the actuators. In order to produce an estimate of φ, designated as ϕ, from the slope measurements $\mathbf{s}$, a relationship must be defined such that

$$\phi = \mathbf{M}\mathbf{s}, \tag{4}$$

where $\mathbf{M}$ is referred to as the reconstructor matrix. Noting that in Eq. (3), the geometry matrix, $\mathbf{A}$, defines the relationship between the measured slopes and the phase, an inversion of $\mathbf{A}$ is used to produce an estimate of $\mathbf{M}$. Least squares estimation is the most common technique due to its minimal complexity performing a pseudoinverse of $\mathbf{A}$, as shown by

$$\begin{aligned} \phi &= \mathbf{A}^{+}\mathbf{s}, & (5)\\ \phi &= (\mathbf{A}^{T}\mathbf{A})^{-1}\mathbf{A}^{T}\mathbf{s}, & (6)\\ \phi &= \mathbf{M}\mathbf{s}. & (7) \end{aligned}$$

The reconstruction matrix, $\mathbf{M}$, which is formed by the geometry matrix is thus unable to form a solution of the waffle mode in the reconstruction of the phase. Noise in the wavefront sensor measurements and misregistration can cause the waffle to develop. Therefore the subapertures located on the edge of the sensor are particularly prone to develop the waffle first due to the lower illumination levels and subsequent lower signal-to-noise ratios in those areas. The waffle pattern can then accumulate over the DM in a closed-loop feedback system because the sensor cannot sense the mode for compensation. A Laue-type diffraction pattern can form in the image plane of the system when the DM is in a waffle mode. This diffraction pattern has been noted to occur when compensating for a star with a regular arrangement of spots over long exposures.[5]

2.2 Detecting the waffle in DM commands

The waffle mode is not developed in the reconstructed phase using the SH WFS and Fried sampling geometry and therefore cannot be detected in the phase space using this configuration. Though due to the nature of the accumulation on the deformable mirror, discussed in Section 2.1, the waffle shows up in the commands being sent to the actuators to form that pattern.[6] The commands to the DM can then be used to determine the amount of the mode that is within the AO system because ultimately the checkered pattern appears there.

Consider the 3 x 3 matrix, **W**, that have values that are in the form of a waffle arrangement,

$$\mathbf{W} = \begin{bmatrix} 1 & -1 & 1 \\ -1 & 1 & -1 \\ 1 & -1 & 1 \end{bmatrix}.$$

This waffle matrix, **W**, contains a pure checkered pattern and is used to evaluate how much of this formation occurs on the deformable mirror command by correlation. The commands, $\mathbf{C}(m,n)$, that are sent to the deformable mirror are two-dimensionally cross-correlated using MATLAB ©, with the pure waffle matrix, **W**, as shown by

$$\mathbf{V}(i,j) = \sum_{m=0}^{M_c-1} \sum_{n=0}^{N_c-1} \mathbf{C}(m,n) \cdot \mathbf{W}^*(m+i, n+j), \tag{8}$$

where **V** is the cross-correlation matrix, (i,j) are the corresponding actuator positions for **V**, (m,n) are the actuator coordinates for the commands sent to the DM, and (M_c, N_c) are the dimensions of **C**. The magnitude of **V** at the actuator positions indicates the strength of correlation to the waffle pattern at different areas across the DM. A threshold, δ_w, is used as an indicator of the strength of correlation to waffle. The threshold is determined by purposely inducing the waffle mode onto the AO system and determining the strength of the the mode that begins to degrade the system in terms of Strehl ratio. The areas that are strongly correlated to the waffle mode and surpass the threshold are designated as a waffled region and the number of regions are summed together to form a metric for the amount of waffle on the DM, as shown by,

$$\mathbf{V}_w(i,j) = \begin{cases} 1 & , \mathbf{V}(i,j) \geq \delta_w \\ 0 & , \mathbf{V}(i,j) < \delta_w \end{cases}, \tag{9}$$

$$V_w = \sum_j \sum_i \mathbf{V}_w(i,j). \tag{10}$$

The waffle number, V_w, provides a useful metric for determining the amount of the checkered pattern that accumulates on the DM, while the waffle matrix, $\mathbf{V}_w(i,j)$, gives the spatial location of where the waffle is accumulating on the DM. This research is using spatial filtering techniques on the entire DM when it is applied, therefore V_w is used as the general metric to determine the effectiveness of the filtering. Future research will apply a localized spatial filter to specific areas of where the mode is developing so the waffle matrix $\mathbf{V}_w(i,j)$ can be used as the indicator of when and where to apply the mitigation technique.

3. SPATIAL FILTERING OF DM COMMANDS

Spatially filtering the deformable mirror commands gives the option to maintain a conventional reconstructor while still having the ability to intermittently mitigate the waffle mode when it occurs. Thereby, maintaining the high frequency content in the phase that corresponds to the mode. For the experiments in this paper, a spatial filter with a Gaussian profile, $\mathbf{G}$, as shown by

$$\mathbf{G} = \begin{bmatrix} 0.0113 & 0.0838 & 0.0113 \\ 0.0838 & 0.6193 & 0.0838 \\ 0.0113 & 0.0838 & 0.0113 \end{bmatrix}$$

was used to alleviate the waffle mode by applying the matrix directly to the commands sent to the DM. The filter, $\mathbf{G}$, is two-dimensionally cross-correlated to the DM commands, $\mathbf{C}(m,n)$, as shown by,

$$\acute{\mathbf{C}}(i,j) = \sum_{m=0}^{M_a-1} \sum_{n=0}^{N_a-1} \mathbf{C}(m,n) \cdot \mathbf{G}^*(m+i, n+j), \tag{11}$$

where $\acute{\mathbf{C}}$ is the spatially-filtered commands, (i,j) are the corresponding actuator positions for $\acute{\mathbf{C}}$, (m,n) are the actuator coordinates for the commands sent to the DM, and (M_c, N_c) are the dimensions of $\mathbf{C}$. An investigation of the form of the Gaussian spatial filter shows that in the case that waffle does occur over the deformable mirror, the correlation of the $\mathbf{G}$ matrix will de-weight the corner actuator positions while maintaining a majority of the data in the center actuator command. The actuators directly to the side of the center actuator are of higher weight in the $\mathbf{G}$ matrix corresponding to the inherent coupling of local actuators on a continuous faceplate deformable mirror.

4. EXPERIMENTAL SETUP

The experiments were conducted at the Atmospheric Simulation and Adaptive-Optics Laboratory Testbed (ASALT) at the SOR, Kirtland AFB, NM. The primary benefit to this laboratory is that experiments can be conducted using repeatable turbulence conditions and is in a well-controlled environment. The optical bench described in Section 4.1 and its corresponding hardware is controlled by a computer console which computes all of the data processes in the AO system. This console allows for programmable processing scripts to be inserted in the data flow of the AO system, giving the ability to spatially filter and monitor the DM commands as well as induce the waffle intentionally, as described in Section 4.2.

4.1 Laboratory bench setup

A layout of the bench and its optics is given in Figure 3. The beam path on the optical table begins with a 1550 nm laser as the source. The beam is propagated through the atmospheric turbulence simulator (ATS) consisting of two phase wheels that are used to simulate the atmospheric conditions, which can be user-defined. The aberrated beam is then reflected off a steering mirror (SM) in order to compensate for the tilt/tip in the beam. The DM then applies a high-order correction to the beam and is controlled by the DM controller. After reflecting off the DM, the beam is then projected through a set of beamsplitters to the SH WFS and self-referencing interferometer (SRI). The SRI is a WFS that can directly measure the phase, but in this research the SH WFS will be used to close the AO loop. The beam is focused and readjusted with the optics within this process to simulate a 1.5 meter AO system.

4.2 Experiment parameters and waffle inducement

The experiments for this research were run using moderate atmospheric turbulence conditions, varied by the ATS. Each data run was conducted for 100 frames of data, where the system speed is scalable. The SM was initiated at frame 5 to alleviate for the overall tilt incident on the DM and commands were sent to the DM at frame 10 to begin mitigating for the higher order aberrations caused by the atmospheric turbulence. The primary metric for this research was not the performance of the AO system in terms of Strehl ratio, but the

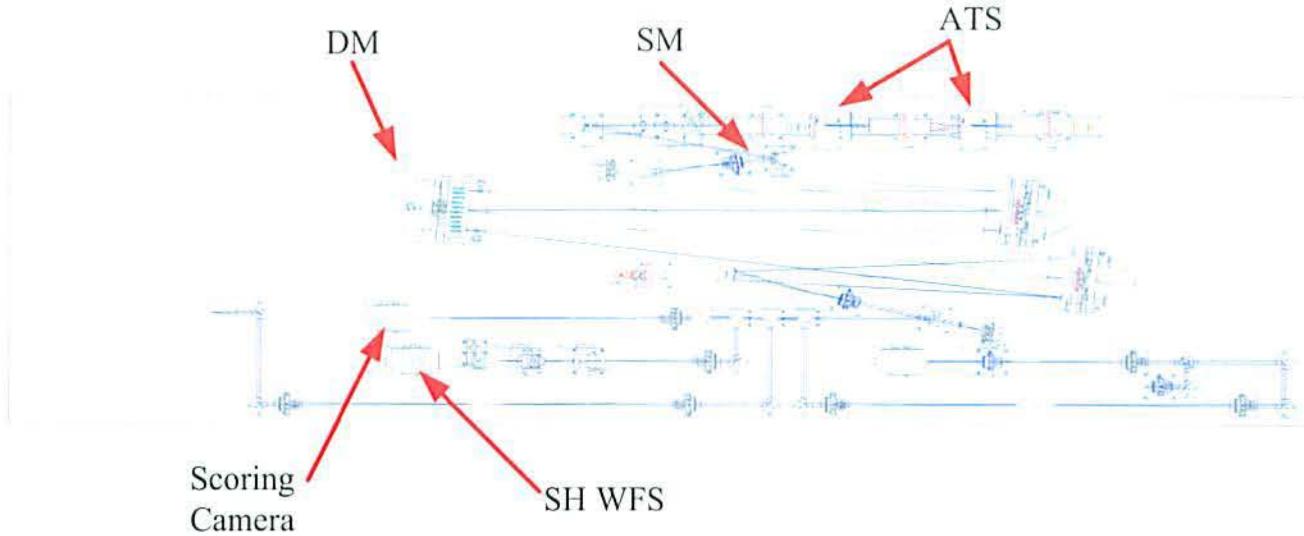

Figure 3. ASALT laboratory's optical table layout in SRI-2.[7]

mitigation of the waffle mode accumulation, V_w, of the DM. Therefore, in order to mitigate the mode in the experiments, the disturbance was added to the system.

There are multiple conditions that are conducive to accumulating waffle on the DM, as mentioned in Section 2. The causes can range from misregistration to high noise levels on the sensor, but for this research a more controlled methodology was required in order to repeat the experiments. Therefore, a waffle pattern was added to the commands sent to the lower right quarter of the deformable mirror with a controlled magnitude of 0.225 μm of stroke from frames 20 to 40.

The controlled nature of the induced waffle disturbance is beneficial due to the repeatability of the condition, yet must be differentiated from the conventional causes that induce the development of the mode internally within operational AO systems. The servo-controller used to produce the DM commands has a leaky integrator gain, a, to dissipate unobserved modes such as the waffle, as shown by

$$c_{k+1} = a\ c_k + b\ \phi_{k+1}, \tag{12}$$

where c_{k+1} is the next command to the DM, c_k is the current command, b is the filter gain, and ϕ_{k+1} is the reconstructed residual phase off the DM. The leaky integrator gain is conventionally set to < 1 so that even if the residual phase was zero and the turbulence was static, the next DM command, c_{k+1}, would not be equal to the current command, c_k. This condition is intentionally set in order to allow unobservable modes to 'leak' out of the closed-loop system. Though, if the causes of the waffle development, such as noise and misregistration, reach a magnitude that can overcome the leaky integrator gain's ability to dissipate the mode, the waffle can begin to accumulate.

5. RESULTS AND ANALYSIS

Figure 4 is a plot of the Strehl ratio and waffle number, V_w, of the closed-loop AO system using a turbulence condition with a Fried parameter of $r_0 = 10.85$ cm. The waffle pattern was induced onto the DM, as mentioned in Section 4.2, and began to degrade the system performance at frame 20 as the mode began to accumulate. The Gaussian filter was not applied in this data run and the unwanted mode was allowed to continue to spatially propagate across the DM. The waffle inducement stops at frame 40 and V_w begins to slowly dissipate over time because the leaky integrator gain in the servo-controller is set to, $a = 0.99$. The dissipation is a characteristic of the method used to artificially place the waffle on the DM, as mentioned in Section 4.2. The optical bench used in this research has low noise levels and was carefully aligned so when waffle was no longer commanded

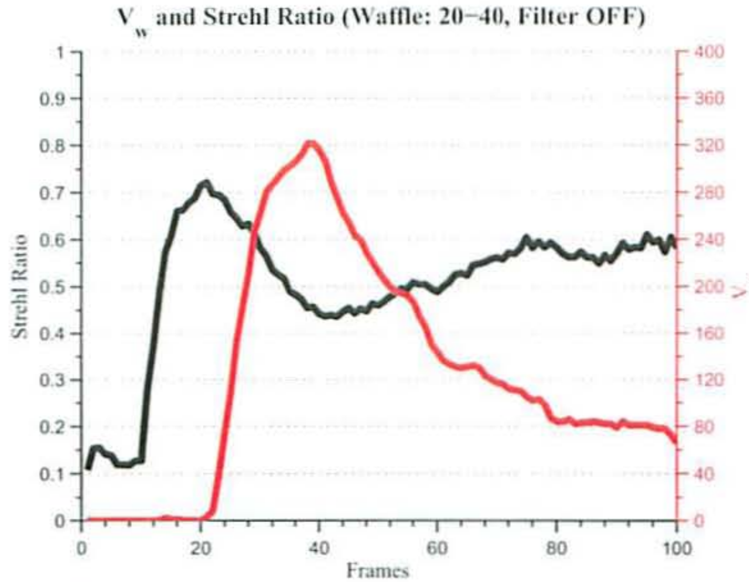

Figure 4. Strehl ratio and waffle accumulation (V_w), r_0 = 10.85 cm. The spatial filter is not turned on this data run.

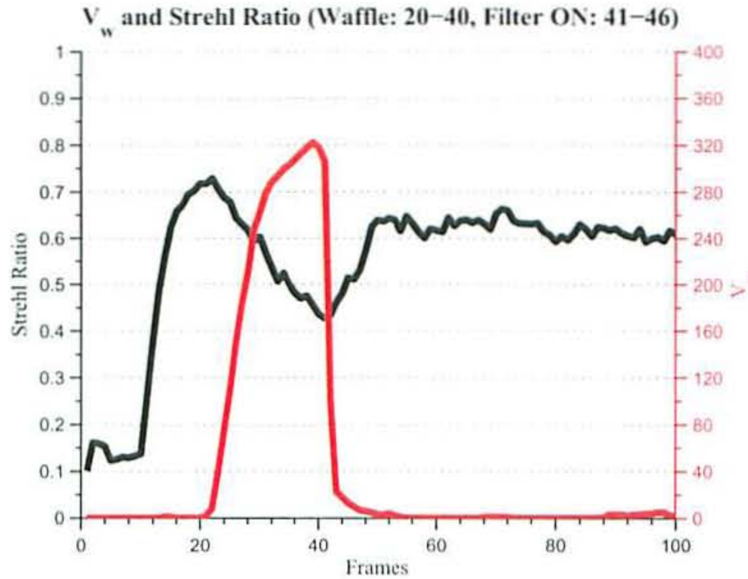

Figure 5. Strehl ratio and waffle accumulation (V_w), r_0 = 10.85 cm. The spatial filter is turned on and dissipates the waffle.

at frame 40, the leaky integrator gain was able to gradually decrease the amount of the unobserved mode. The commanded waffle in these experiments show the effects it has on the performance of the system, as shown by the decrease in Strehl ratio in relation to the magnitude of the mode's development.

The same experimental conditions were repeated in another data run except the spatial filter was activated between frames 41-46 which began at the peak accumulation point of the waffle, as shown in Figure 5. The spatial filter is applied for five frames and then disengaged. Figure 6a displays the commands being sent to the DM at the maximum waffle accumulation point. The mode's checkered appearance is distinctively apparent and is verified with a $V_w = 318$, signifying a large correlation to waffle on the DM commands, as shown by Figure 6c. Spatially filtering the commands between frames 41-46 dissipated the waffle while retaining the lower frequency content of the phase. Figures 6b and 6d show the commands being sent to DM at frame 45 and the amount of

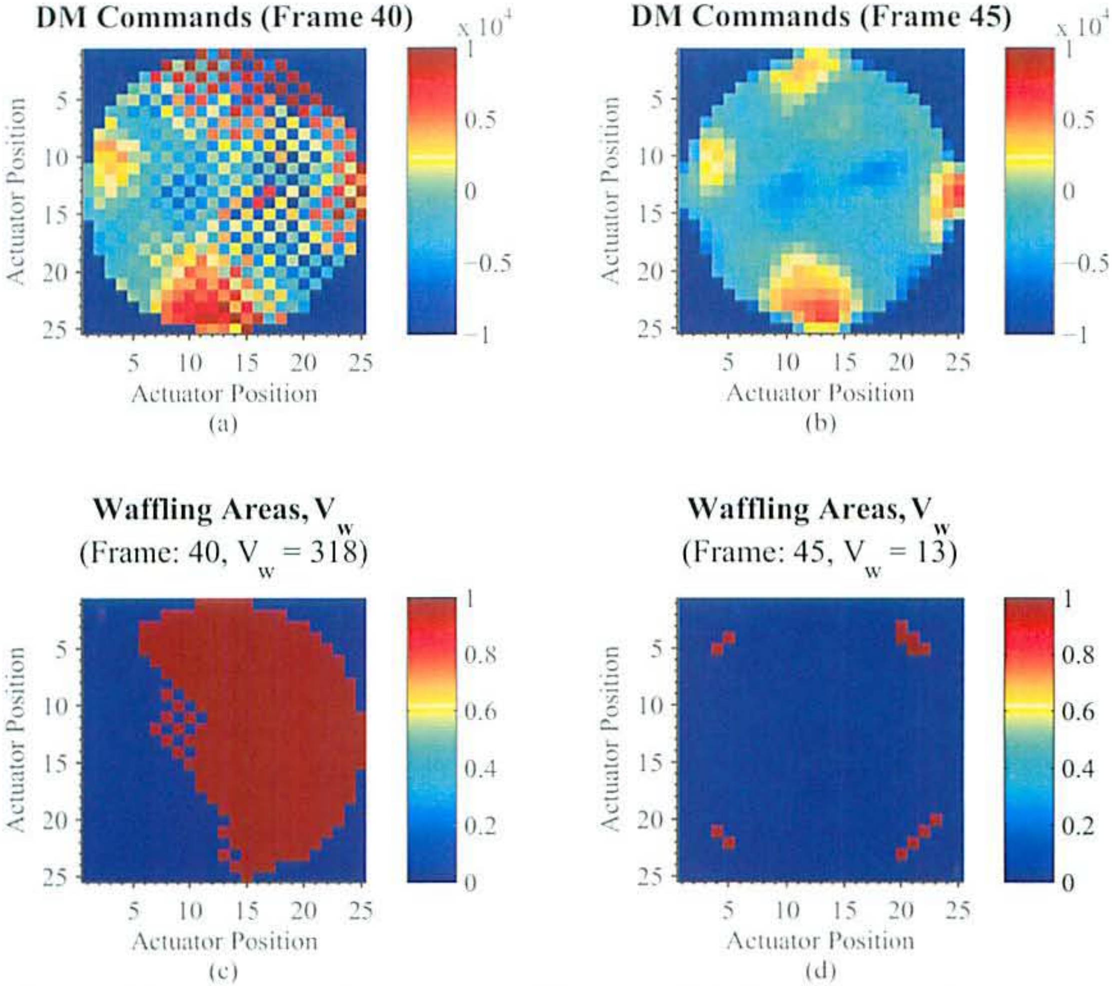

Figure 6. Display of the commands and corresponding waffle accumulation (V_w) on the deformable mirror, r_0 = 10.85 cm.

diminished waffle with a $V_w = 13$, respectively. The ability to maintain most of the information of the commands allows the AO system to remain closed, yet clears out the unwanted mode to a negligible magnitude.

The mean Strehl ratio of the AO system using the turbulence conditions in Figures 4 and 5, without introducing waffle or filtering, is approximately 0.6. Frames 80-100 on each data run have similar Strehl ratios, though each have different accumulations of waffle. Figure 4 has an average $V_w = 80$ over these frames, while Figure 5 has a negligible amount of waffle. This suggests that the AO system has a threshold to the mode which it can operate under before there is a major degradation in the performance of the system. This analysis can be used to determine how much waffle accumulation, V_w, is acceptable before the system should be actively spatially filtered and/or suggest an adjustment in δ_w.

6. CONCLUSION

This paper discusses a technique to detect and mitigate the waffle mode in the commands sent to the DM using a conventional adaptive-optics system. The mode is unobservable in the phase space using a SH WFS and Fried sampling geometry, but because the waffle pattern ultimately develops on the commands, it can be monitored in the DM space. A waffle metric, V_w, was defined in Section 2.2 which describes how strongly the DM commands are correlated to a waffle pattern. This metric was used to measure the effectiveness of spatially filtering the DM commands as a method to alleviate the waffle. The detection and mitigation techniques were experimentally tested and verified on a closed-loop AO system in the ASALT laboratory. The spatial filtering technique does not require any additional hardware and was shown to be highly effective at mitigating for the mode in closed-loop operation. This analysis suggests that the technique is a viable option for alleviating waffle in operational AO systems and will be pursued further in future research.

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